Excerpt from June 2004 Fermilab Physics Advisory Committee Recommendations

The Neutrino Program

Introduction

The Committee heard several presentations on the status of the present neutrino program, proton economics, and a summary of a Director's Review which covered neutrino projects worldwide. There were also oral presentations and substantial new materials submitted by the NOνA collaboration. This section summarizes this information, gives the Committee's findings about the NOνA proposal, and concludes with some recommendations.

The physics case for NOνA must be assessed within the context of the international program in neutrino physics. It is both fortunate and timely that the American Physical Society is conducting a multi-divisional study of the neutrino physics program in the United States and its international context. The Committee heard an oral presentation on the current status of the APS study. The Committee hopes that its assessment of the NOνA proposal will provide useful input to the APS study, and looks forward to the recommendations from the APS study, which are expected to be available in August 2004.

The discovery of neutrino mass and mixing has raised very interesting questions about neutrino physics: How many different types of neutrinos are there? What are the masses of the neutrinos, and to what new, very high mass scale do they point? What is the pattern of mixing among the different neutrino species? Is there a CP-violating difference between neutrino and antineutrino oscillation? If there is, are neutrinos the key to understanding the matter-antimatter asymmetry of the universe?

The question of whether there are more than three types of neutrinos is currently being addressed. If there are only three, then the neutrino spectrum consists of two mass eigenstates, ν_1 and ν_2, that participate in the evolution of solar neutrinos, plus a third one, ν_3, that is a key player in the evolution of atmospheric neutrinos. The spacing between ν_1 and ν_2 is much smaller than that between them and ν_3. The coupling of ν_3 to electrons, described by a mixing angle θ_{13}, is known to be smaller than the other couplings, but it is not known *how* small. Given that two other measured angles, θ_{12} and θ_{23}, are large, most models predict sizable θ_{13}.

We do not know whether the ν_1 - ν_2 "solar pair" is lighter than the isolated neutrino ν_3 (a normal hierarchy), or heavier than it (an inverted hierarchy). Quarks and charged leptons have two lighter states closer in mass, hence this configuration is referred to as the normal hierarchy. Grand unified theories generically predict a normal hierarchy, while an inverted spectrum would suggest a new underlying symmetry. Thus, whether the neutrino mass spectrum is normal or inverted is a very interesting question.

The physical effects that can establish that neutrino oscillation does violate CP, and those that can discriminate between a normal and an inverted spectrum, both depend on the size of θ_{13}.

Thus, determining the rough value of this angle is an important step on the road to the exploration of CP violation and of the nature of the spectrum.

Taken together, the measurement of θ_{13}, the determination of the normal or inverted character of the neutrino mass spectrum, and observation of CP violation in neutrino oscillation will form a very fundamental and important program of exploring physics beyond the Standard Model. Fermilab can play a leading role in this program.

Current Status and Future of Neutrino Beams at Fermilab

At present, the Laboratory is running one neutrino experiment, MiniBooNE, in the Booster neutrino beamline and is preparing to commission the NuMI beamline for the MINOS experiment. After major improvements in the performance of the Booster, including substantial reduction in the losses per protons delivered, the 8 GeV Booster beamline is now running at a rate of 10^{19} protons on target/week. A total of 3×10^{20} protons have been delivered to MiniBooNE, and the experiment should receive a total of 5×10^{20} protons by early 2005. The Committee congratulates the Accelerator Division on these improvements, and also recognizes the efforts of the MiniBooNE and MINOS collaborations.

NuMI commissioning is proceeding on schedule, with first beam extraction expected in December 2004 and substantial neutrino production starting in the first quarter of 2005. The Booster has already demonstrated the ability to produce enough protons for both NuMI running and antiproton production. However, once NuMI turns on, the number of protons delivered to the 8 GeV beamline will be substantially reduced. A program of improvements to the Booster complex was outlined. The improvements could provide the capability for some beam to Booster neutrino experiments during the NuMI era.

As the NuMI beamline turns on, the MINOS experiment should begin accumulating neutrino events. The far detector has been operational since 2003 and is taking data with cosmic rays, while the near detector is more than 50% assembled and should be ready for first beam at the start of 2005. The MINOS program will concentrate on ν_μ disappearance and will also have some sensitivity to $\nu_\mu\rightarrow\nu_e$ if $\sin^2 2\theta_{13}$ is close to 0.1.

The report of the Fermilab Long Range Planning Committee presents a vision of a future neutrino program. This vision includes further oscillation measurements with the Booster, if MiniBooNE results lead in that direction, and a program of low-energy neutrino cross section measurements useful to oscillation measurements and interesting in their own right. The vision also outlines a series of steps in a long-term oscillation program following MINOS. These steps include:

1. An experiment designed to measure θ_{13} with a sensitivity to $\sin^2 2\theta_{13} \sim 0.01$ and to determine the mass hierarchy if θ_{13} is not too small;

2. A proton driver that would enable the sensitivity to $\sin^2 2\theta_{13} \sim 0.005$, and enable determination of the mass hierarchy and the search for CP violation;

3. A possible second detector on the second oscillation maximum; and

4. A possible future Neutrino Factory.

In this approach, each step would be guided by the results of earlier steps. The Committee endorses this long-range vision and its implementation via a step-wise campaign to discover non-zero θ_{13}, followed by more precise measurement of $\sin^2 2\theta_{13}$, determination of the mass hierarchy, and search for CP violation.

A proton driver would raise the beam power available from the Main Injector by a factor of five, to 2 MW. Two technologies are being considered for the proton driver. One approach is similar to the existing linac and synchrotron, while the other is an 8 GeV superconducting linac. Either undertaking would greatly expand the physics capabilities of the Fermilab complex.

World-wide Context

In Europe, the experiments ICARUS and OPERA of the ongoing long-baseline (730 km) CNGS (CERN to Gran Sasso) neutrino oscillation program will soon search for ν_τ appearance in a ν_μ beam. Although not optimized for the measurement of $\sin^2 2\theta_{13}$[1], OPERA will be capable of establishing an upper limit on $\sin^2 2\theta_{13}<0.06$[2] on a timescale of ~2011. ICARUS, if funded for its complete detector, will be able to set a comparable limit. Proposed 50% improvements to proton intensity would lower this upper limit by ~20%. In Europe, a Superconducting Proton Linac (SPL), beta beams, and a megaton-scale detector are being studied for a long-range oscillation program starting some time after 2015.

The approved and funded T2K (Tokai to Kamiokande) experiment in Japan, after five running years in its Phase 1, could have the capability to discover ν_e appearance for values of $\sin^2 2\theta_{13}>0.018$[3] by ~2014 if the full intensity is obtained quickly after the turn-on. If $\sin^2 2\theta_{13}$ is smaller, then T2K may be able to set an upper limit as low as $\sin^2 2\theta_{13}<0.006$[4] on the same timescale. In Phase 2 (T2K-II), which involves substantially increased neutrino intensity and a megaton-scale water Cherenkov detector dubbed Hyper-Kamiokande, T2K's $\sin^2 2\theta_{13}$ discovery potential will extend down to 0.002[5], and in the absence of a ν_e signal its upper limit will be pushed down to $\sin^2 2\theta_{13}>0.001$[6]. Because of its relatively short baseline (295 km), T2K is not very sensitive to matter effects, and therefore cannot determine the mass hierarchy on its own.

There is a conceptual study of a wideband on-axis beam and 500-kton water Cherenkov detector with a ~2000 km baseline from Brookhaven. In this approach, a single experiment

[1] The neutrino beam has E=17GeV in order to operate above tau threshold; consequently, the L/E of CNGS is not at the ν_μ oscillation maximum.
[2] At 90% confidence level assuming $\Delta m^2=2.5\text{x}10^{-3}$ ev^2.
[3] Discovery at $\geq 3\sigma$, assuming $\Delta m^2=3.0\text{x}10^{-3}$ ev^2.
[4] At 90% confidence level assuming $\Delta m^2=3.0\text{x}10^{-3}$ ev^2.
[5] Discovery at $\geq 3\sigma$, assuming $\Delta m^2=3.0\text{x}10^{-3}$ ev^2.
[6] At 90% confidence level assuming $\Delta m^2=3.0\text{x}10^{-3}$ ev^2.

would observe multiple oscillation peaks and resolve θ_{13}, the mass hierarchy, and CP violation. It is not clear, however, if the neutral current background can be suppressed to an adequate level. This experiment may require a different detector technology, such as a liquid argon TPC, and/or a slightly off-axis beam.

Reactor oscillation experiments, which measure anti-ν_e disappearance, are capable of directly measuring $\sin^2 2\theta_{13}$ without the ambiguities imposed by the mass hierarchy uncertainty or by CP effects. Future experiments at reactors will aim at limits on $\sin^2 2\theta_{13}$ comparable to that of T2K, and are likely to be systematics-limited within a few years of running. A disappearance signal, if detected, may be difficult to establish without confirmation. Numerous reactor experiments are in the planning stages worldwide. The Double-CHOOZ experiment in France, whose Letter of Intent has been accepted, will be capable of an upper limit of $\sin^2 2\theta_{13}<0.02$[7]-0.03[8] on a timescale of ~2013, with first results of $\sin^2 2\theta_{13}<0.04$[9] in ~2009. Other possible reactor experiments may reach upper limits on $\sin^2 2\theta_{13}$ of 0.01-0.02. Once approved and funded, the timescales for construction and running of reactor experiments can be somewhat faster than long-baseline experiments. Future experiments at reactors may have results available as soon as 2011-2012. Thus, reactor oscillation experiments are roughly competitive in sensitivity and timescale with measurements from T2K. Limits on $\sin^2 2\theta_{13}$ from the reactor experiments depend only on Δm^2, while long-baseline experiments probe combinations of $\sin^2\theta_{23} \times \sin^2 2\theta_{13}$, matter effects, and CP effects. Therefore, reactor measurements are complementary to long-baseline measurements.

P-929 Proposal to Build an Off-Axis Detector to Study $\nu_\mu \rightarrow \nu_e$ Oscillations in the NuMI Beamline – NOνA (John Cooper / Gary Feldman)

The NOνA (NuMI Off-axis Electron ν Appearance Experiment) collaboration submitted a proposal to the Laboratory for consideration at the April, 2004 PAC meeting. The NOνA collaboration is a strong team consisting of over 150 physicists from 34 institutions. There is significant overlap with the MINOS collaboration. They propose the construction of a 50 kton, sampling detector built from particleboard and liquid scintillator with APD readout. The detector would be located above ground, with a long baseline of ~800 km and an off-axis displacement of ~12 km from the main NuMI beamline.

Additional written and presented materials were submitted at the June, 2004 PAC meeting to address questions raised by the PAC, to further quantify and refine the physics case, and to describe the ongoing R&D program. The collaboration also presented the preliminary design of an attractive alternative detector based on a totally active liquid scintillator design (TASD). Simulations of this option show an improvement in efficiency of almost a factor of two, and a cost per mass that is roughly double that of the sampling calorimeter. Better background rejection capability and improved energy resolution may give this option better overall sensitivity.

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[7] At 90% confidence level assuming relative error of σ=0.2% between near and far detectors, Δm^2=2.0x10^{-3} ev^2.
[8] At 90% confidence level assuming relative error of σ=0.6% between near and far detectors, Δm^2=2.0x10^{-3} ev^2.
[9] At 90% confidence level assuming Δm^2=2.0x10^{-3} ev^2.

Physics Case for NOνA

To establish a compelling physics case, NOνA must meet the following criteria:

1. Uniqueness.

   NOνA must have a unique physics capability not achieved by any other experiments worldwide.

2. Competitiveness with T2K.

   NOνA must compete with T2K, the Japanese program discussed above, within a similar time frame.

3. Competitiveness and/or complementarity with future experiments at reactors.

   NOνA must compete in sensitivity with reactor experiments, or provide information not obtainable by reactor experiments.

4. Capability for evolution with a future neutrino program.

   NOνA must allow a natural progression to CP violation studies with a future proton driver with the currently proposed detector at the same location.

In the near future, NOνA is the only experiment in the world that can potentially determine the mass hierarchy, albeit for a limited range of parameters. Its performance is competitive with T2K in other areas, namely the search for electron appearance for $\sin^2 2\theta_{13} \geq 0.01$ and precision measurements of $\sin^2 2\theta_{23}$ and Δm^2_{23}. A measurement of $\sin^2 2\theta_{13}$ in Europe that is competitive with those of NOνA and T2K on the timescale of their running without proton drivers is not foreseen. NOνA's electron appearance signature, which will be statistically limited, is complementary to the disappearance signature from the reactor experiments, which will be systematically limited and insensitive to matter effects and CP violation. Once electron appearance is found, it will make a strong case for a proton driver and possibly a second detector. The Committee finds the proposal meets the above four criteria if the detector can be built in a timely manner.

Following construction of a proton driver, the NOνA detector, possibly augmented with a second off-axis detector, would achieve its full physics reach, able to determine the mass hierarchy for any value of the CP-violating phase δ provided $\sin^2 2\theta_{13} \geq 0.02$. Such a determination would in turn allow 3 sigma discovery of CP violation for a large range of δ. In combination with the data from T2K-II, it would extend the reach in CP violation to much smaller $\sin^2 2\theta_{13}$.

How soon must NOνA start taking data in order to be timely? T2K will come online in 2009 using the existing SuperKamiokande detector and ramping up the new beamline over a four-year period. The situation is reversed for NOνA, since the NuMI beam will be in routine operation, whereas the detector must be built. NOνA can start data-taking with a near detector and a partial far detector (~15%), then increase the detector volume continuously thanks to its modular structure. The Committee concludes that NOνA must start data-taking in the same time frame as T2K, and complete the far detector within four years to meet this criterion. An early start for data-taking is essential because the sensitivity improves most rapidly in the first year or two of operation. That is, the most critical aspect of timeliness is when the data-taking starts, not when detector construction finishes. The Committee notes that the timely construction of NOνA is inconsistent with the present budget projection of the Laboratory.

In the context of a coherent long-range neutrino program, the Committee finds the case for NOνA compelling. The physics goals are to first measure $\sin^2 2\theta_{13}$, then to resolve the mass hierarchy and possibly discover CP violation in neutrino oscillations. This approach is attractive, proceeding in incremental steps that allow for decisions based on outcomes at each stage of the program, taking into account new results from other experiments, as well as funding constraints. A coherent vision for the long-term program, together with clear decision points, strengthens the case for NOνA.

Recommendations

The Committee strongly endorses the physics case for the NOνA detector, and would like to see NOνA proceed on a fast track that maximizes its physics impact. Both the physics case and the detector design have undergone rapid evolution since the PAC first received the NOνA proposal. While the Committee applauds this progress, it concludes that Stage I approval at this time is premature. The collaboration should first complete the following steps:

1. Finalize the choice of detector design, mass, and location.

   The totally active scintillator design looks very promising. If it is chosen, a revised proposal will be required for the Committee to recommend approval, as well as for the subsequent levels of approval the experiment must secure.

2. Complete the proposed R&D program.

   A demonstration of the photo-electron yield for a full-length cell of the chosen detector design is necessary; this is a key parameter underlying all of the physics simulations. Measurements of APD performance and detailed noise studies are important, and further engineering studies for the TASD option are also needed, if this option is selected. Evaluation of the cosmic ray background should also be done. The Committee is also interested to know how the construction schedule could be optimized for rapid initial start with a partial detector.

3. Update the proposal to reflect the complete science case.

   The revised proposal should include all the new information presented at the June, 2004 PAC meeting. A more complete discussion of possible neutrino measurements beyond $\sin^2 2\theta_{13}$ is also desirable (e.g., improved determination of $\sin^2 2\theta_{23}$, neutrino scattering cross section measurements with the near detector, etc.).

The Committee strongly endorses the proposed R&D plan and urges the Laboratory to provide adequate support for timely completion of this program. The NOνA collaboration should be encouraged to report back as soon as the above items are addressed. This would be the time for consideration of Stage I approval. In addition, the Committee recommends that the collaboration work together with the Fermilab directorate and the larger neutrino community to:

4. Develop a coherent vision for a future proton driver-based neutrino program, with NOνA as the first step.

   Such a vision would be consistent with the report of the Fermilab Long Range Planning Committee report. The APS neutrino study will be released in a few months, and should provide the context for a coherent national program of neutrino physics. The next step is to establish clear priorities and to work with the funding agencies to make this program a reality. The Committee believes that both NOνA and a proton driver should play an important role in this future program.

5. Explore accelerated funding mechanisms.

   The window of opportunity that achieves NOνA's scientific impact in a timely fashion is inconsistent with the availability of new construction funding in the Fermilab budget projection. In this projection, significant money for new initiatives is not available until FY 2010 at the earliest. The Committee encourages the Laboratory to work together with the funding agencies to put the necessary funding profile in place for a construction start in FY 2007, or in FY 2008 at the latest.